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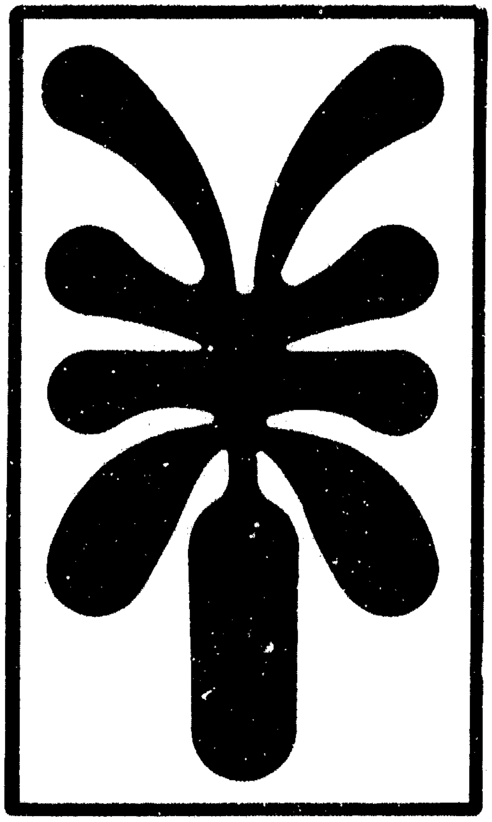
FLUIDICS



Basic Components and Applications

by James W. Joyce

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Since its discovery at Harry Diamond Laboratories in 1959, fluidics has gradually been developed into a viable technology. This report provides a description of fluidic components and systems now in use or ready for use in many applications. The fluidic technology provides sensing, computing, and controlling functions with fluid power through the interactions of fluid streams. Since fluidics can perform these functions without mechanical moving parts that will wear out, it has the advantages of simplicity and reliability. Other advantages discussed are the low cost, environmental insensitivity, and safety of fluidic systems.

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20. Abstract (Cont'd)

Commercial applications of fluidics are found in the aerospace industry, industrial control, medicine, and personal-use items. The first aerospace application in production in the United States was for the thrust-reverser control for a DC-10 airplane. In industry, fluidics has been applied to air-conditioning controls, machine controls, process controls, and production-line controls. More than 100 different applications have been identified in these areas.

One of the first commercial applications of fluidics was for life-support medical equipment. Several medical devices now on the market incorporate some degree of fluidic control. Personal-use fluidic products include pulsating showerheads, lawn sprinklers, and oral irrigators.

For military use, fluidics has been successfully applied to a fluidic generator to convert pneumatic energy into electrical energy, a fluidic stability augmentation system for helicopters, and a pressure-regulating system for aircraft. Currently under development are rate sensing circuits for roll rate control of cannon-launched guided projectiles and missiles, and a fluidic capillary pyrometer for continuous temperature measurements in high-temperature process control.

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1. INTRODUCTION

The technology known as fluidics provides sensing, computing, and controlling functions with fluid power through the interaction of fluid (liquid or gas) streams. Consequently, fluidics can perform these functions without mechanical moving parts. The inherent advantages of fluidics are, therefore, simplicity and reliability, since there are no moving parts to wear out.

Fluidics—originally called fluid amplification—was discovered in 1959 by a group of scientists at the U.S. Army Harry Diamond Laboratories (HDL). During the first 10 years of its existence, there was a tendency to try to use fluidics in anything and everything, without giving adequate attention to whether it offered any true advantages over existing technologies. This period of trying to over-employ fluidics reached its peak in the mid-1960's. Those days have now passed. Fluidics is no longer a novelty; it can stand on its own merits.

Since 1970, a number of truly valid applications of fluidics have been realized. The areas of use include the aerospace industry, medicine, personal-use items, and factory automation. Fluidics for military systems has also progressed to the point where several systems are in advanced development stages. In most cases, the reason for selecting fluidics has been a combination of low cost, high reliability, inherent safety, and the ability to operate in severe environments.

Almost all early (first-generation) fluidic devices were operated in the turbulent-flow regime. Since the mid-1970's, the emphasis at HDL has shifted to the use of laminar-flow (second-generation) fluidic components. Turbulent flow is characterized by a "noisy" jet as illustrated in figure 1a (p 6); in contrast, laminar flow is characterized by a "quiet" well-defined jet (fig. 1b). Turbulent-flow devices are still used where higher power levels are required. Laminar-flow fluidic devices are used primarily in signal applications where the ability to detect and process extremely small pressure signals is essential.

In the sections that follow, the basic concepts and components of fluidic technology are presented, and the inherent advantages of fluidics are discussed. Finally, the applications of fluidics are highlighted with some specific examples.

2. FLUIDIC COMPONENTS

A wide variety of fluidic components is now available "off the shelf." As might be expected, the components of today are vastly improved over their counterparts of the early 1960's. Figure 2 illustrates the giant strides made in component packaging by comparing an early 1960's prototype unit to a current equivalent off-the-shelf component. Manufacturing techniques have improved, size has been reduced, and unit cost has been lowered. In addition, integrated subsystems have replaced breadboard circuits.

One of the most recent advances in circuit integration techniques has been the adoption by HDL of a standard format, designated C format, for fluidic laminates.[1] This format permits optimal flexibility within its 3.3 by 3.3 cm (1.3 by 1.3 in.) area, and results in a vertical stacking of horizontally laminated elements to build fluidic circuits. Vertical stacking minimizes interconnection distances and volumes, and thereby minimizes signal losses, parasitic impedances, and probability of leaks. Some typical C format laminate configurations are illustrated in figure 3.

Fluidic components are generally classified as sensors, amplifiers, or interface devices. Sensors translate a parameter of interest (for example, angular rate, distance, or temperature) into a pressure/flow signal that can then be processed in a control circuit. Amplifiers perform the logic and control functions. The interface devices transform the signals from the control section of the circuit to an appropriate output (such as electrical display or mechanical motion). Each of the categories of components may be either active or passive. An active fluidic component is one that requires a separate power source in addition to whatever input signals are applied to it. Passive components, on the other hand, operate on the signal power alone. Except for passive circuit components such

[1] *J. W. Joyce, A Catalog of Fluidic C Format Laminates, Harry Diamond Laboratories, HDL-SR-83-2 (March 1983).*

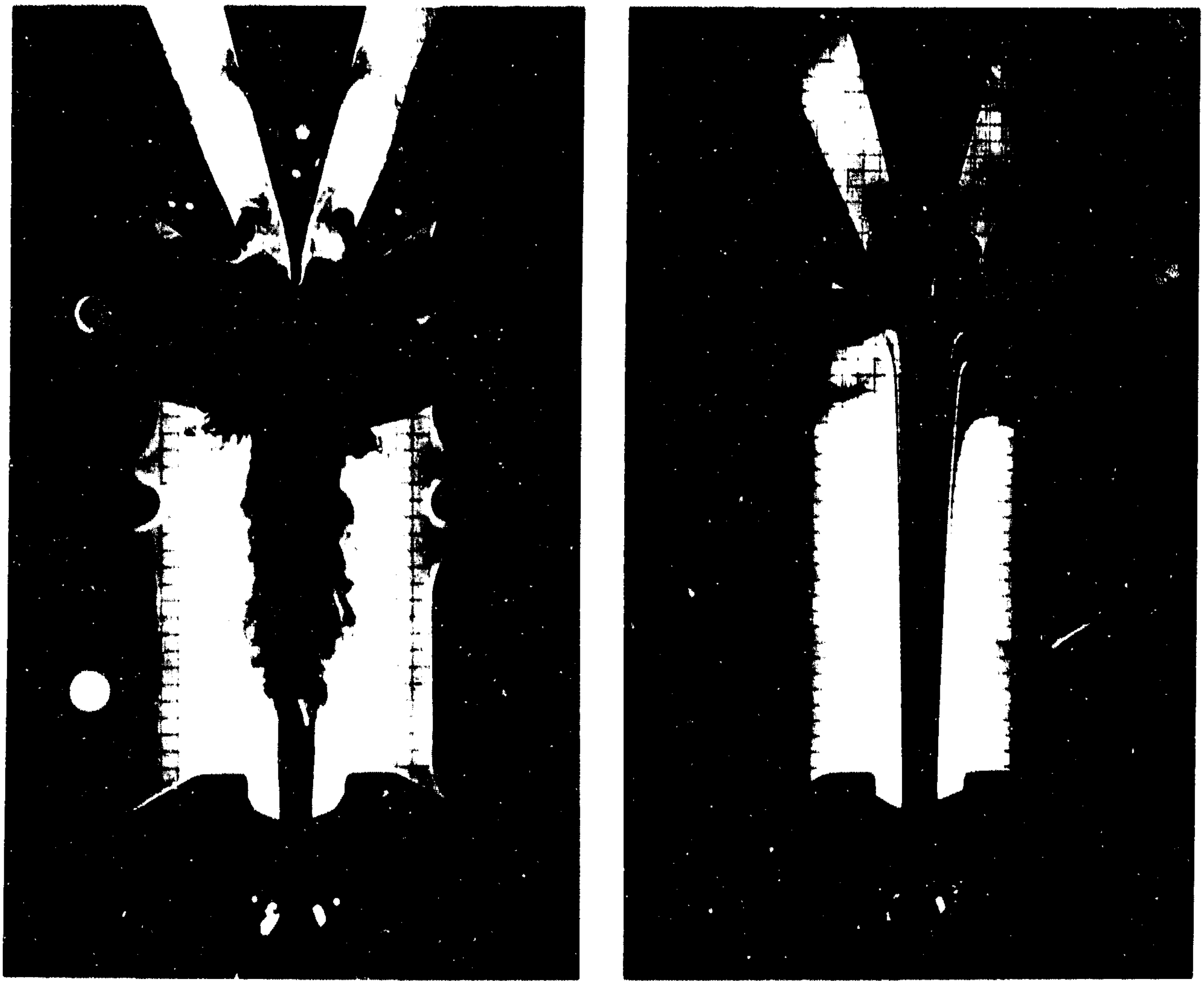


Figure 1. Turbulent and laminar jets.

as fluid resistors and capacitors, almost all fluidic components are active.

2.1 *Fluidic Sensors and Interface Devices*

Many types of sensors and interface devices are available off the shelf. Because of the wide variety of functions offered by these components, they are not discussed in detail here.

L. M. Sieracki[2] presents a comprehensive, albeit somewhat outdated, cataloging of fluidic

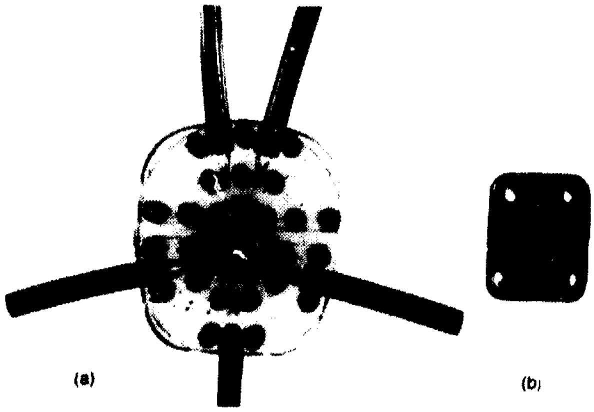


Figure 2. Fluidic hardware: (a) early prototype and (b) current.

[2] *L. M. Sieracki, Handbook of Fluidic Sensors, Lorelei Corp., contract with Harry Diamond Laboratories, HDL-CR-77-787-1 (May 1977).*

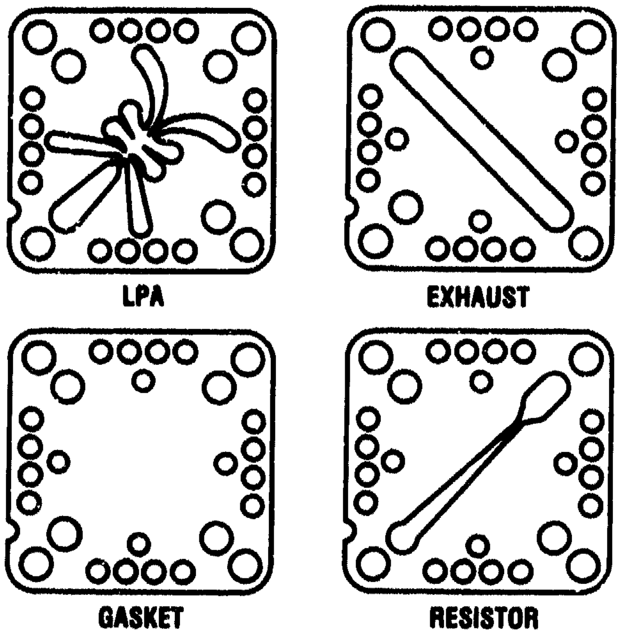


Figure 3. Some typical C format configurations.

sensors—both off-the-shelf items and those still in research and development at the time the survey was made. Some of the parameters that can be sensed fluidically include

- angular rate and acceleration,
- jerk ≡ d (angular acceleration)/dt,
- position,
- strain,
- speed,
- concentration/density,
- sound level,
- flow rate,
- pressure, and
- temperature.

Among the most commonly used sensors for industrial applications is a family of noncontact position sensors. These devices sense the distance to an object (analog type) or simply the absence or presence of an object (digital type). For military (and civilian) control systems, one of the sensors with the greatest potential is the laminar jet angular rate sensor (LJARS).[3] The LJARS can replace expensive mechanical rate gyroscopes in many applications. A silhouette of a typical LJARS is shown in figure 4.

[3] *T. M. Drzewiecki and F. M. Manion, Fluerics 40: The Laminar Jet Angular Rate Sensor, Harry Diamond Laboratories, HDL-TM-79-7 (December 1979).*

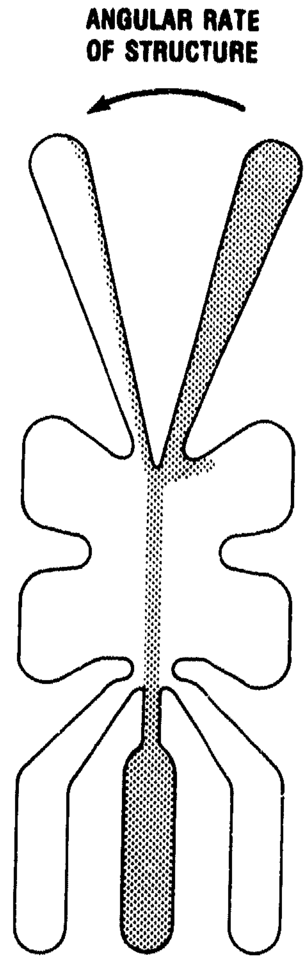


Figure 4. Silhouette of fluidic LJARS.

The most often used interface devices include those that produce mechanical or electrical outputs. Others yield pressure/flow outputs in a different medium or at a significantly different (usually higher) level than that of the control circuit. Examples of the latter type of interface device are low-pressure piloted spool or diaphragm valves in which the pilot signals are supplied by the fluidic control circuit. The high pressures controlled by the spool or diaphragm valve may be used to actuate a cylinder or other mechanical device.

2.2 *Fluidic Amplifiers*

Most fluidic amplifiers have at least four basic functional parts. These include (1) a supply port, (2) one or more control ports, (3) one or more output ports, and (4) an interaction region. These

are illustrated in figure 5. These sections may be compared, respectively, to the cathode, control grid, plate, and interelectrode region of a vacuum tube. Many amplifiers also contain vents to isolate the effects of output loading from control flow characteristics. The sound of air escaping from such vents gives many fluidic amplifiers their characteristic hiss or whistle.

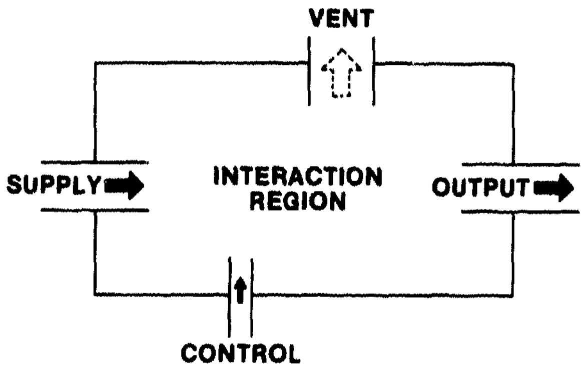


Figure 5. Schematic diagram of basic fluidic amplifier device.

The supply jet in the fluidic amplifier passes into the interaction region where it is directed toward the output port(s) or receiver(s). Control flow injected into the interaction region determines the direction and distribution of the supply flow, which in turn affects the flow reaching the receiver(s). The amount of pressure or flow recovery available in a receiver is determined by the internal shape of the device. Useful amplification occurs inasmuch as change in output energies can be achieved with smaller changes in control energies.

In general, a fluidic amplifier may be categorized in either of two ways: by the function it performs or by the fluid phenomenon that is the basis for its operation. Categorized by function, amplifiers are either analog (proportional) or digital (bistable). Identifying amplifiers by fluid phenomena produces the following major categories:

- jet deflection,
- wall attachment,
- impact modulation,
- flow mode control, and
- vortex flow.

2.2.1 *Jet-Deflection Amplifiers*

In jet-deflection (or beam-deflection) amplifiers, one or more control ports are constructed perpendicular to the supply jet (fig. 6). The direction of the supply jet is thus altered by flow issuing from the control port. This type of control results in proportional or analog performance, since the jet deflection is continuously varied (over a limited range) from one output receiver to the other.

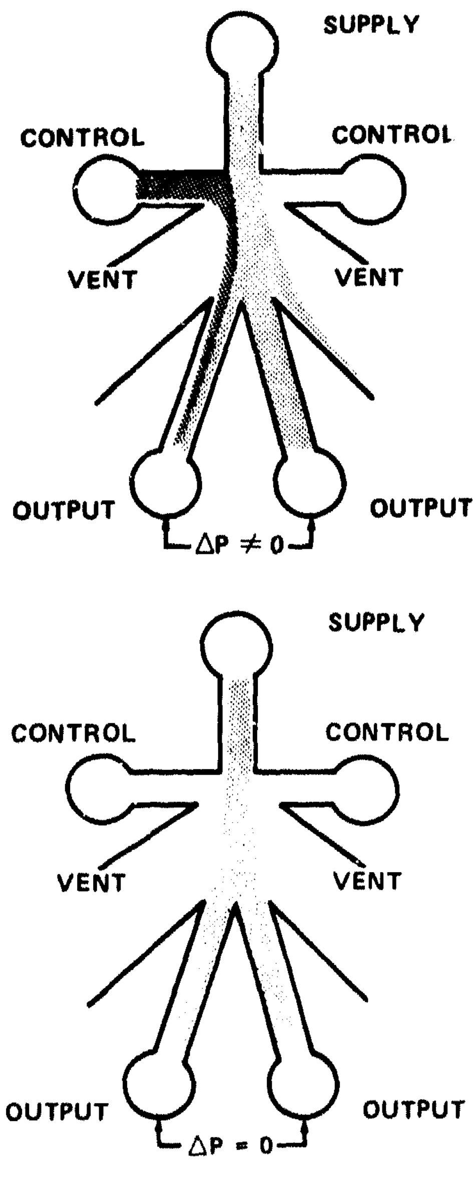


Figure 6. Jet-deflection fluidic proportional amplifier.

In all early forms of the analog jet-interaction amplifier, the flow was turbulent. This condition imposed limitations on the signal-to-noise levels and dynamic ranges available with such amplifiers. More recent research work at HDL has produced the laminar proportional amplifier (LPA).[4,5] Typically, an LPA exhibits a pressure gain of about 10, a dynamic range of over 1000, and a bandwidth ranging from 100 to 1000 Hz, depending on the supply pressure. The addition of the LPA to the inventory of available fluidic components has increased the potential uses for fluidic systems where analog control is required. A silhouette of the standard HDL LPA showing the normalized (in terms of the nozzle width, b_s) critical parameters is illustrated in figure 7.

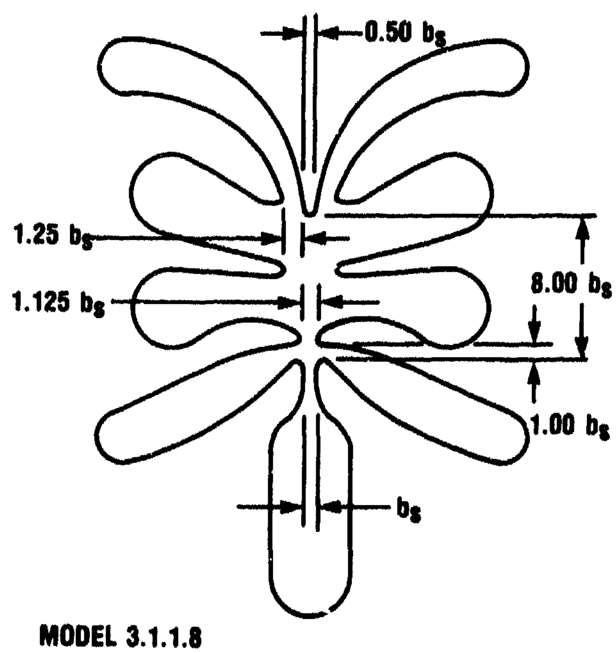


Figure 7. Silhouette of HDL standard LPA.

Of particular significance has been the ability of the LPA to take low-level pressure output signals from fluidic sensors and amplify them to levels that are more easily and economically transduced. This in turn has increased the number of fluidic sensors that can now be used successfully. A number of fluidic LPA gain blocks for such uses have been documented by Drzewiecki.[6]

Not only can the LPA be used as an analog device, but also LPA's with positive feedback can be used to perform most of the common digital logic functions, as Mon[7] has demonstrated. Preliminary test results indicate that power consumption can be reduced by a factor of 10 or more if LPA's are substituted for equivalent turbulent digital logic elements.

2.2.2 *Wall-Attachment Amplifiers*

A typical two-dimensional wall-attachment amplifier is depicted in figure 8. This first-generation device has a supply nozzle, control ports, two walls set back from the supply nozzle,

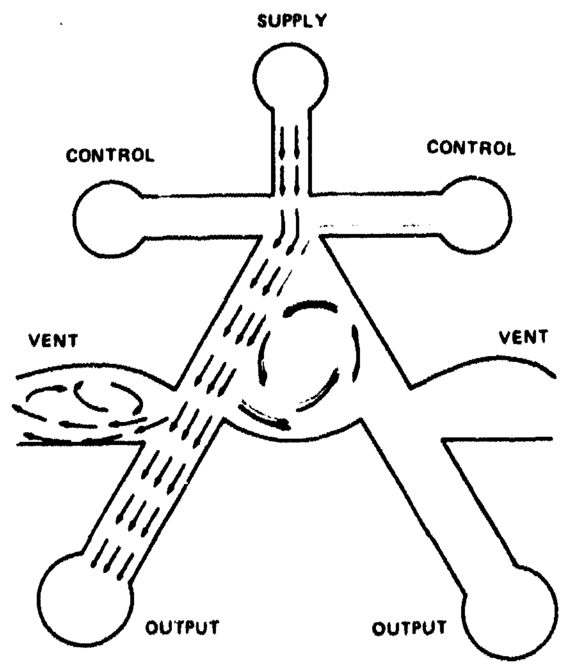


Figure 8. Wall-attachment fluidic bistable amplifier.

[4] *F. M. Manion and G. Mon, Fluerics 33: Design and Staging of Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TR-1608 (September 1972).*

[5] *T. M. Drzewiecki, Fluerics 38: A Computer-Aided Design Analysis for the Static and Dynamic Port Characteristics of Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TR-1758 (June 1976).*

[6] *T. M. Drzewiecki, Fluerics 42: Some Commonly Used Laminar Fluidic Gain Blocks, Harry Diamond Laboratories, HDL-TM-82-10 (September 1982).*

[7] *G. Mon, Basic Design Concepts of Laminar Fluidic Digital Logic Elements Using Laminar Proportional Amplifiers with Positive Feedback, Trans. ASME, J. Dyn. Sys. Meas. Control, 101, 1 (March 1979), 77-80.*

and output receivers. The Coanda effect—a turbulent jet's property of attaching itself to a wall—causes this device to be bistable. The issuing turbulent jet attaches to one of the walls downstream of the control ports and subsequently flows into the corresponding output receiver. The jet will remain attached to this wall until a sufficient pressure signal is applied to the control port on that side. This signal will inject enough fluid into the low-pressure bubble formed by the attached jet to raise the pressure at that point and switch the jet to the opposite wall. In this manner of operation, digital performance is achieved. When one output receiver is "on," the other is "off." Variations in the geometrical configurations of this basic device yield elements that can produce most of the common digital logic functions—flip-flop, AND, OR/NOR, and so on. In addition, an oscillator can be made by providing a feedback loop from each output receiver to its corresponding control port.

2.2.3 *Impact Modulation Amplifiers*

When two opposed round supply nozzles direct jets along the same axis at one another, an impact plane is formed at some point between the two nozzles. This is the basis for the performance of impact modulator devices. As one jet is weakened relative to the other, the impact plane will move toward the weakened jet nozzle. One resulting configuration that uses this phenomenon is the transverse impact modulator shown in figure 9. Here, the two opposed jets have an orifice plate between them. If the impact plane is initially to the right of the orifice plate, it tends to seal off the orifice, and a positive pressure at the output is realized. However, as control flow is injected, the jet on the left is weakened, the impact plane moves to the left side of the orifice plate, and the pressure at the output drops to ambient or slightly below. Thus, a digital logic function is achieved at the output.

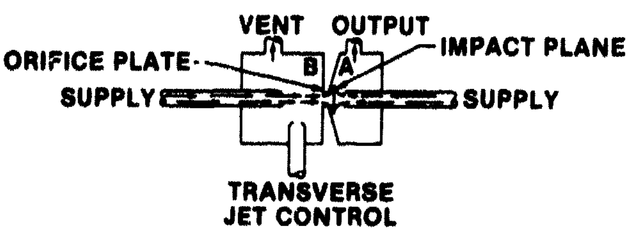


Figure 9. Transverse impact modulator.

Another configuration of this type of device is known as the summing impact modulator (SIM). In the SIM, one of the two opposed jets is maintained constant, and the other is varied to cause the impact plane to shift. The SIM produces an analog output.

2.2.4 *Flow Mode Control Amplifiers*

This class of fluidic amplifiers makes use of the laminar-turbulent flow phenomenon. In such devices, the supply jet will be laminar in the absence of any control signal, and flow will be directed toward an output port, as depicted in figure 10a. Because the flow is laminar, a significant portion of the jet will reach the output receiver and produce an output signal. If the jet is disturbed, such as by the injection of transverse control flow (fig. 10b), the jet changes from laminar to turbulent flow, and virtually no flow reaches the output receiver. Thus, when the control signal is applied, there is no output signal. In essence, this device—known as as turbulence amplifier—is an OR/NOR gate. In addition to pressure/flow, the control signal may be acoustic; this phenomenon is the basis for a class of fluidic acoustic sensors.

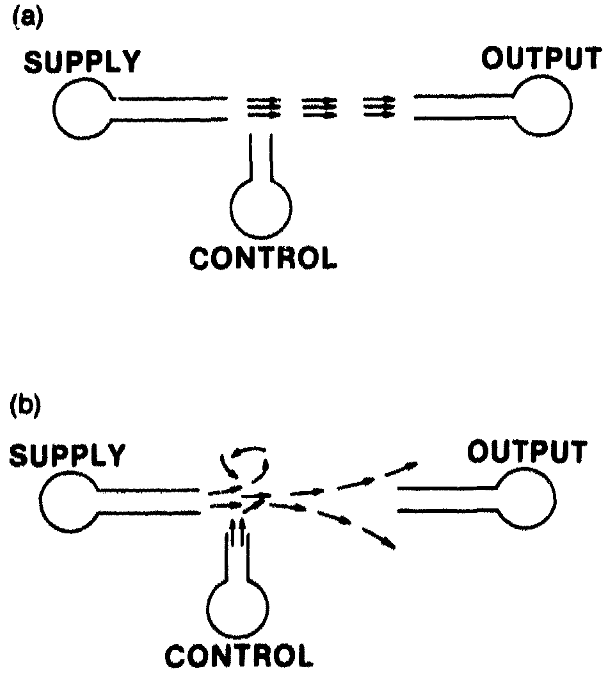


Figure 10. Flow mode control amplifier: (a) without control signal and (b) with control signal applied.

2.2.5 *Vortex Flow Amplifiers*

In the vortex flow device, flow from the power nozzle is directed radially inward in a shallow cylindrical chamber, as shown in figure 11. In the absence of any control flow, the supply flow continues radially inward toward the outlet, or drain, at the center of the chamber. If the control flow is injected tangentially, the supply flow and control flow combine to produce a swirl-type flow pattern which becomes a forced vortex field. The pressure gradient across the chamber produced by this forced vortex field alters the magnitude and the pattern of the supply flow. Specifically, as control flow is increased, the supply flow is decreased, so that the device acts as a throttling valve. This same principle is the basis for the operation of the vortex angular rate sensor. Here, no control flow is introduced; instead, the swirl is imparted by the angular rotation (about the axis of the drain) of the chamber itself. Differential pressure signals from an angle-of-attack detector in the drain (or in the chamber near the drain) correspond to the angular velocity of the sensor.

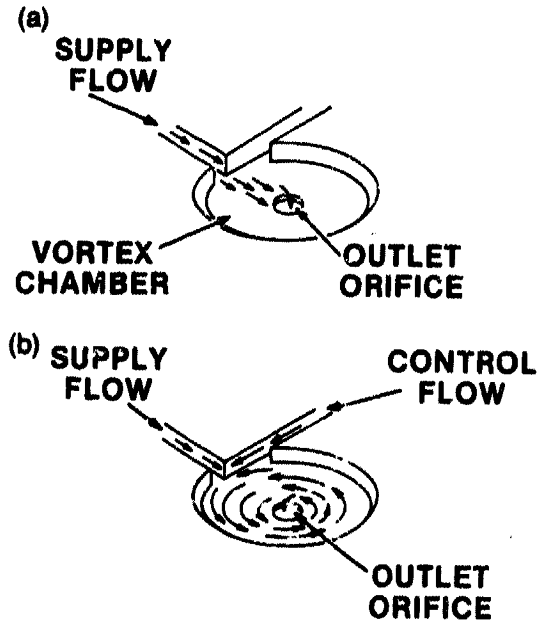


Figure 11. Vortex flow amplifier: (a) without control flow and (b) with control flow.

3. ADVANTAGES OF FLUIDICS

The fact that the basic elements of fluidics, as described in section 2, contain no moving mechanical parts and require no electricity leads to numerous inherent advantages of this technology for controls applications. Among these advantages are the following.

- High reliability: Since there are no moving parts to wear out, the normal wear-out types of failures are essentially nonexistent. Some specific examples of proven high reliability of fluidic systems are discussed later in this report.

- Low cost: In most uses, fluidic systems have a lower initial cost than competitive equivalents. In addition, the high reliability and low maintenance of fluidics, combined with low initial cost, result in total life-cycle costs that are extremely low when compared with alternatives.

- Environmental insensitivity: Fluidic components and systems can be designed so that the effects of environmental stresses (shock, vibration, acceleration, temperature, altitude, etc) are minimal. Fluidics also has superior tolerance to the effects of nuclear or electromagnetic radiation.

- Safety: Fluidic systems require no special explosion proofing, since they are inherently safe. This advantage makes fluidic systems particularly desirable for applications such as munitions loading or process controllers involving corrosive or explosive chemicals.

In addition to the four major advantages cited above, fluidics offers a wide variety of sensing functions, some of which are unique. Fluidic systems are generally small and lightweight compared to most other competitive control systems. And the speed of operation, while nowhere near as fast as electronics, is nevertheless considerably faster than mechanical or conventional moving-part pneumatic/hydraulic systems.

4. COMMERCIAL APPLICATIONS OF FLUIDICS

The applications of fluidics are too numerous to list completely. Consequently, this report only addresses several representative applications, both civilian and military, from different fields.

In general, fluidics applications have been realized in machine controls, process controls, production-line controls, air-conditioning controls, aerospace systems, medical equipment, and personal-use items. Although only a limited number of military fluidic systems are "in the field," several systems are in advanced development stages and offer high promise for eventual field use.

4.1 *Aerospace*

The first production aerospace fluidic application in the U.S. was for the thrust-reverser actuator controls for the General Electric CF-6 engine for the McDonnell Douglas DC-10 aircraft. This system was placed in revenue service in August 1971. (The same control system on the same engine is also used on the European A300B Airbus.) The fluidic thrust-reverser hardware is shown in figure 12. The fluidic system controls the thrust-reverser actuator air motor speed after 90 percent of the actuation stroke and also limits the torque at the end of the stroke. To achieve these functions, a fluidic operational amplifier, providing lag-lead compensation, accepts the appropriate speed or torque-limiting signal and drives a mechanical servovalve that, in turn, actuates the snubbing valve and brake on the air motor as required to maintain proper control. The actuator and controls must operate in the temperature range from −40 to 177 C (−40 to 350 F). The supply gas for the fluidic circuitry is engine-compressor bleed air at a maximum temperature of 315 C (600 F).

Actual performance data for this system have demonstrated a mean time to failure (MTTF) in excess of 600,000 hours.[8] This value is based on about 5,500,000 hours of component operating time. An indication of the impact of the reliability of the fluidic controls on the overall thrust-reverser system is illustrated by the following data. From maintenance data on the DC-10, the Boeing 747, and the Lockheed L-1011 thrust reversers, the values for mean time between unscheduled removals (MTBUR) and total component flight hours are presented in table 1.[8] These values show that the MTBUR for the thrust-reverser system using fluidics on the DC-10 is more than double that of the other two systems that use conventional pneumatically controlled actuators.

Table 1. Conventional versus Fluidic Reliability Comparison

Complete thrust-reverser system	MTBUR	Component total flight hours
Conventional pneumatic		
Boeing-747 fan thrust-reverser	4035	16,028,680
Lockheed L-1011 thrust-reverser	3742	2,252,589
Fluidic		
McDonnell Douglas DC-10 thrust-reverser	9510	6,114,618

Other fluidic commercial applications in aerospace include the thrust-reverser and secondary nozzle actuator control systems on the Concorde SST and pressure ratio and variable inlet guide vane controls for the Rolls-Royce RB211 engine on the Lockheed L-1011 aircraft.

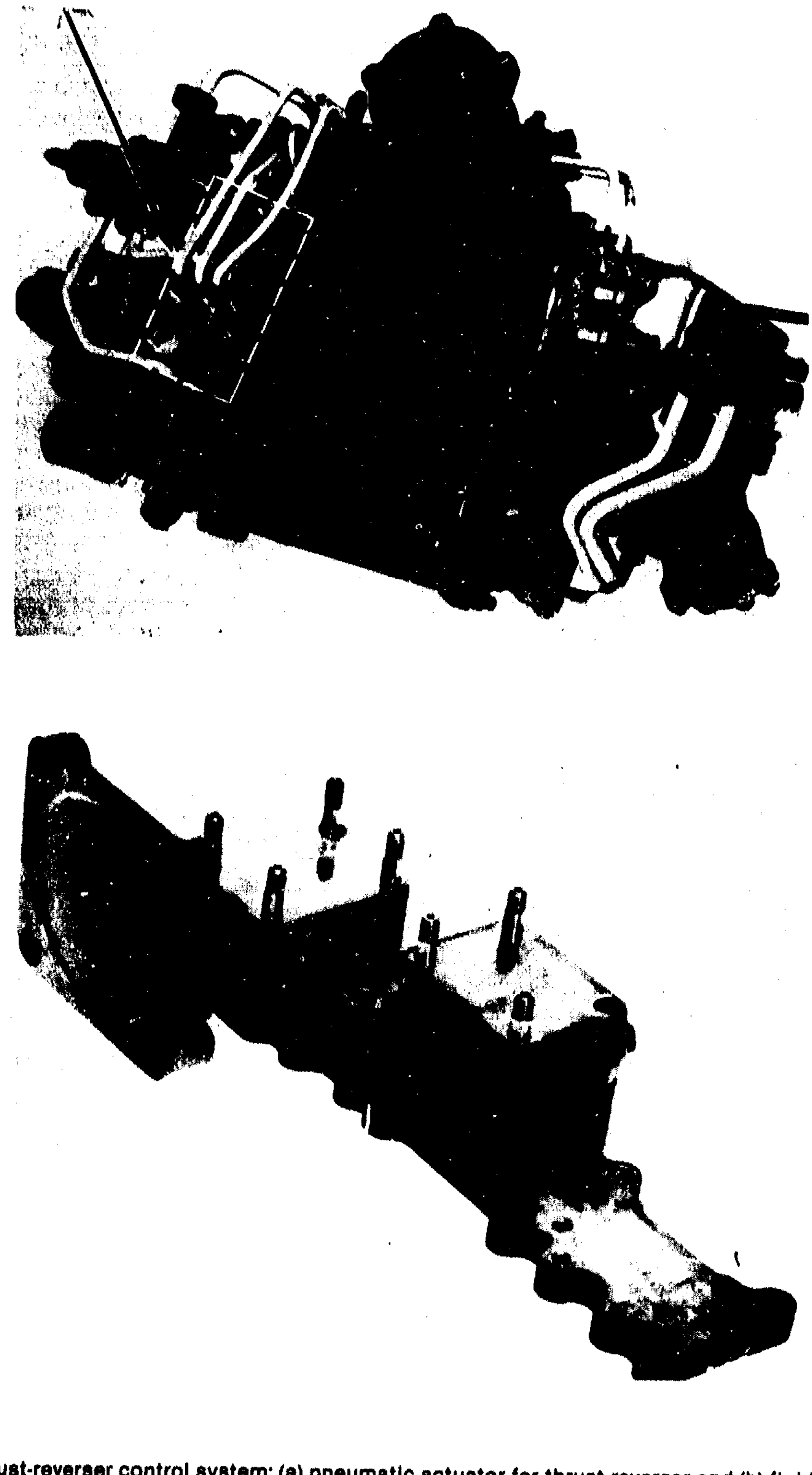
4.2 *Industrial Control*

Included in this category of fluidic applications are air-conditioning controls, machine controls, process controls, and production-line controls. Over 100 different applications have been identified from these areas of use in the U.S. and abroad.

Fluidic controllers for large-scale air-conditioning systems (for example, in office buildings) have been in service since the late 1960's. These units control the flow of air through

[8] *W. T. Fleming and H. R. Gamble, Reliability Data for Fluidic Systems, AiResearch Manufacturing Company of Arizona, contract with Harry Diamond Laboratories, HDL-CR-76-092-1 (December 1976).*

fluidic control module



(a)

(b)

Figure 12. Fluidic thrust-reverser control system: (a) pneumatic actuator for thrust reverser and (b) fluidic control module.

the complex ducting circuit of the air-conditioning system. One such controller is shown in figure 13. This particular unit uses three summing impact modulators to achieve proportional control.[9] Inputs to the controller are pressure signals that represent parameters such as temperature and relative humidity. Another type of controller uses a three-stage jet-interaction fluidic proportional amplifier in a unit that gives positive assurance of fan operation in the forced-air system and, at the same time, eliminates the need for any pneumatic-electric interface. Over 100,000 fluidic controllers for air-conditioning systems have been sold and installed by several manufacturers, making this the most widely used application of a fluidic system.

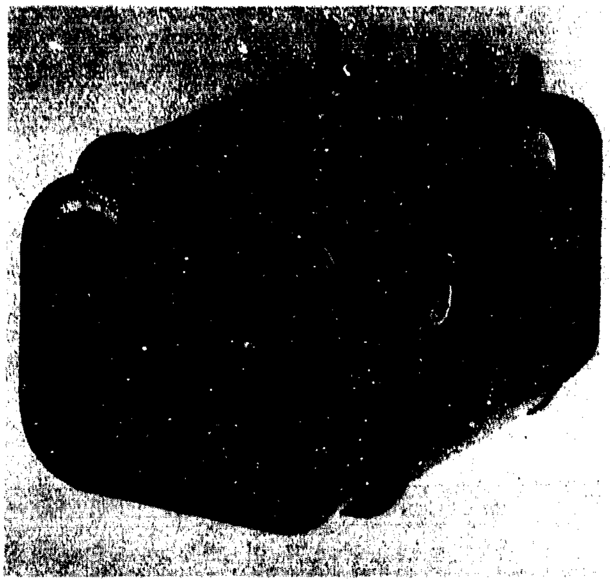


Figure 13. Fluidic air-conditioning controller.

Machine-control applications include the control of industrial sewing-machine attachments. In one such attachment, a fluidic control system senses the leading and trailing edges of a garment moving through a sewing station.[10] The system then controls the attachment to cut a continuous thread chain and/or binding flush with the edge of the garment. The fluidic circuitry includes interruptible jet sensors that detect the edges of the garment and 12 logic elements to perform the control function. Fluidics was selected for this use because it could perform the required operation more accurately and reliably than competitive approaches. Other machine-control applications include sequencing controls for turret lathes and sensing/control systems for die protection.

An example of the use of fluidics in process controls is the application of a fluidic diverter valve (fig. 14) to control liquid level. These diverter valves are wall-attachment devices with a single control port. Flow normally issues out of one output leg of the valve; when a control signal is applied, the flow is diverted to the opposite leg. This type of valve was installed in a paper and pulp plant in 1964 to control the level in a white water (paper stock with a 0.5-percent consistency) chest.[11] The valve, which is still in operation, maintains the proper level by adding waste condensate water whenever the chest level is low. The only maintenance required on this valve has been an occasional cleaning of the control tube to remove pulp deposits.

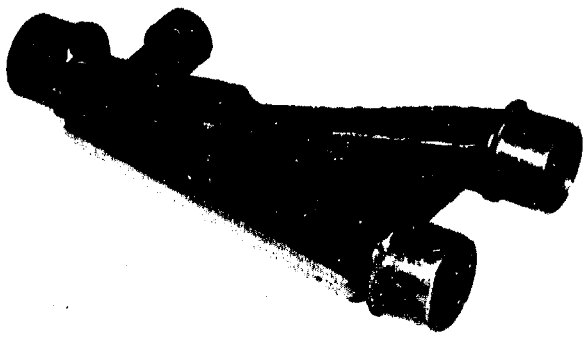


Figure 14. Fluidic diverter valve.

Another application of fluidics for process controls is a set-point proportional controller that is used to control the flow of steam in a fiber-texturing process.

A good example of fluidics in production-line controls involves the use of the controller shown in figure 15. This controller unit is a fluidic air-gauging comparator circuit that detects

[9] *J. A. Enright, The Impact Modulator Meets the Market, Fluidics Quarterly, 3, 3 (1971).*

[10] *Corning Glass Works, Fluidic Product Department, Fluidics Case History, Data Sheet FCH-2B (1971).*

[11] *R. B. Adams, Some Industrial Process Applications of Fluidics, Fluidic State-of-the-Art Symposium, V (30 September to 3 October 1974), 91-117.*

variances from the user's preset quality standards. The controller can be used with a variety of available sensors. With these sensor/controller combinations, tolerances as low as 0.0001 in. (0.0025 mm) can be readily and accurately monitored. The output of the controller can be either electric or pneumatic. Many of these in-line fluidic control systems are being used by numerous companies in a variety of specific applications.

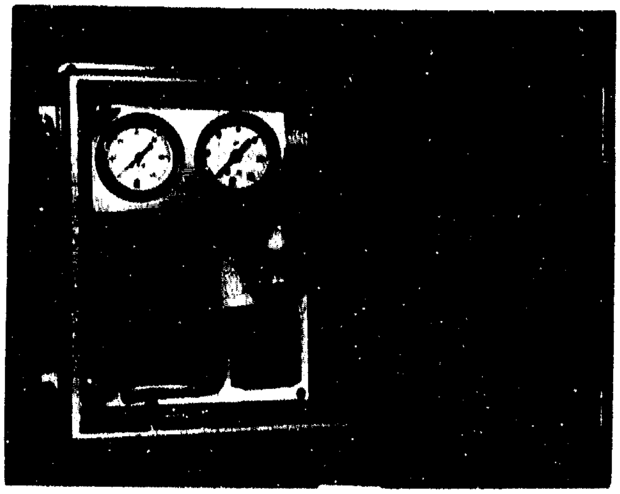


Figure 15. Fluidic controller.

4.3 *Medicine*

Investigating the feasibility of using fluidics in life-support medical equipment was one of the first research and development efforts undertaken at HDL in the early 1960's. Because of the high reliability of fluidics, the technology was considered a strong contender for items such as pulsatile extracorporeal blood pumps and respirators, both of which involve controlling the movement of fluids. Today, several medical devices on the market incorporate some degree of fluidic control.

The leading candidate for fluidic controls to date has been respirators, in which fluidic controls have been used in several different types. The chief advantages of fluidics in respirators are increased reliability over conventional pneumatic controls and inherent safety. Respirators are, of course, normally used in areas where high oxygen levels require explosion-proofing of any electrical equipment. Consequently, many respirators have been designed to operate directly from either oxygen or air supplies that are commonly available in hospitals. Such respirators thus become natural candidates for fluidic controls.

4.4 *Personal-Use Items*

One of the first fluidic personal-use items to appear on the market was a pulsating showerhead (fig. 16). A manually controlled valve, operated by twisting the barrel of the showerhead, provides two modes of operation. One mode is a continuous steady stream, as in any conventional showerhead. In the other mode, a fluidic oscillator produces a pulsating flow out of each of two rectangular slots in the face of the showerhead. This pulsating flow produces a massaging action.

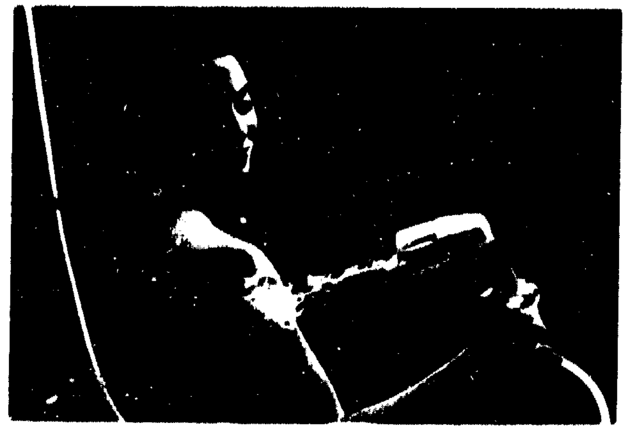


Figure 16. Fluidic pulsating showerhead.

Other personal-use fluidic products include a family of fluidic lawn sprinklers and oral irrigators. In the former, the back and forth action of the sprinkler to sweep an area of the lawn is achieved without mechanical moving parts. The oral irrigator is similar to the showerhead in that it provides a pulsating flow to massage the gums and enhance the rinsing action.

Most recently, fluidic windshield washers first appeared as standard equipment on two 1979 automobile models. Today, the vast majority of new cars made in this country are equipped with fluidic windshield washers. A single fluidic oscillator (or two oscillators on some larger cars) replaces the

conventional two-nozzle configuration. With the fluidic washer, the wiper blades are no longer responsible for distributing water because the oscillator output sprays the entire windshield surface in a fan-like pattern. In addition, the oscillator nozzle produces droplets that are larger than those from the conventional system and are consequently less affected by wind.

5. MILITARY APPLICATIONS OF FLUIDICS

Maintenance and logistics costs are extremely high in a military system's life cycle, and almost all such systems must operate through environmental extremes; hence, a military system has to be rugged. As a result, the military is interested in fluidics because of its reliability and environmental insensitivity. Low initial cost, another military concern, can be realized by the use of fluidic systems.

The fluidic generator (fig. 17), an interface device that converts pneumatic energy into electrical energy, has been type classified in a Navy system. In this application, the fluidic generator ingests ram air and converts it to electrical energy to supply the total electrical power requirements of a bomblet dispenser system. The aircraft must be flying above a specified velocity in order for the generator to operate; therefore, no electrical power is available below the specified velocity. Hence, fluidics is used as an environmental safety system by allowing the pilot to activate the dispenser only if the aircraft is flying at or above the specified velocity range. The Army recognized the potential of using the fluidic generator as an inexpensive means of furnishing the total power requirements of an electronic fuze. In addition, safety is enhanced, since no power is generated unless the projectile is in flight. These advantages have led to the selection of the fluidic generator for the Army's Multiple Launch Rocket System.

Within the military, the Army and Navy have cosponsored a development program for a fluidic stability augmentation system (SAS) for helicopters. The SAS assists the pilot by providing rotational damping about one or more axes. A single-axis fluidic SAS is shown in figure 18. The SAS uses a vortex angular rate sensor that senses the rate of turn of the aircraft in a particular axis. The fluidic signal from the rate sensor is amplified by several jet-interaction fluidic porportional amplifiers, shaped dynamically by passive fluidic RC-networks and then converted into mechanical motion by means of conventional hydraulic servoactuators. The SAS uses the on-board hydraulic power supply to operate the fluidic circuitry. This system is low-cost, easy to maintain, and more reliable than electrohydraulic or electromechanical equivalents.

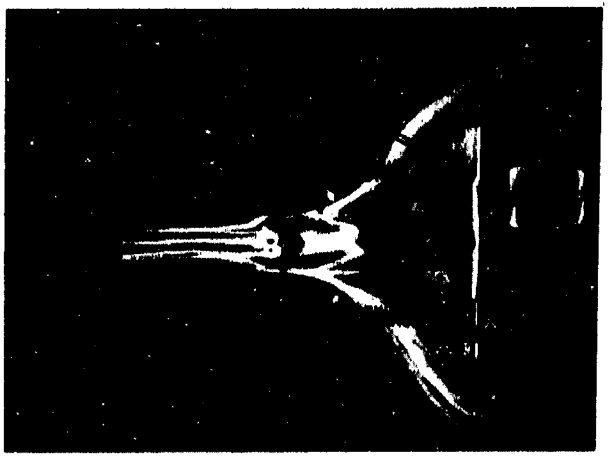


Figure 17. Fluidic generator.

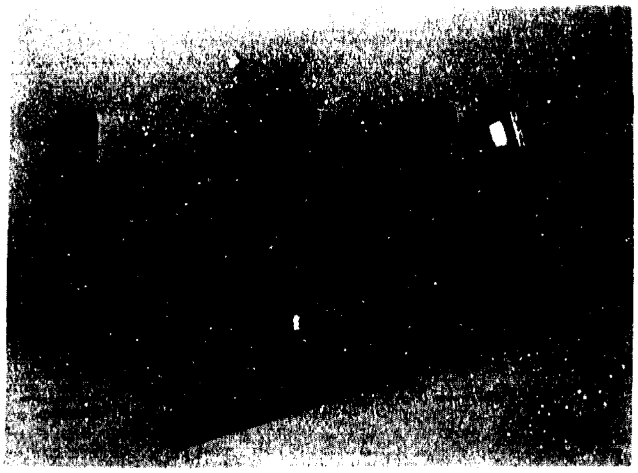


Figure 18. Fluidic single-axis stability augmentation system.

A series of flight tests for the fluidic SAS on the Army's OH-58 helicopter (using a two-axis SAS) and the Navy's TH-57 helicopter (using a single-axis SAS) produced over 12,000 hours of total air-

craft flight time.[12] From these tests, the measured mean time between failures (MTBF) for the fluidic SAS was 4,557 flight hours. Since the failures experienced during these tests of prototype SAS's are considered to be about 90-percent correctable, the estimated MTBF for final production units is about 25,000 to 50,000 flight hours. Investigations have shown that the electromechanical flight-control equipment on the Army's Huey Cobra helicopter has exhibited MTBF of about 140 flight hours. By comparison, the fluidic SAS prototype MTBF is more than 30 times greater than that of the Huey Cobra system, which is considered to be a mature one. These data, together with those from the DC-10, clearly demonstrate that fluidic systems are extremely reliable.

Another fluidic application that has demonstrated high reliability is the pressure-regulating system for the Navy's S-3A aircraft. The system, shown in figure 19, controls the coolant air for the aircraft avionics. A similar regulating system is also used on the Navy's F-18 airplane.

The first development program based on second-generation fluidics involved stabilizing the gun tube on a tank. The resulting two-axis stabilization system used the LJARS together with LPA gain blocks as the heart of the sensing and controlling circuitry.[13] This system was successfully demonstrated on an M48A5 tank in April 1979. Overall performance of the fluidic system equalled or exceeded that of the electrohydraulic system currently in use on the tank.

From the results of the gun stabilization program, fluidic rate sensing circuits are now being developed for roll rate control of cannon-launched guided projectiles and missiles. The complete rate sensing circuit consists of (1) an electrically driven pump to supply air to the fluidic circuit, (2) an LJARS with several (usually two or three) stages of LPA's, (3) a transducer to convert the fluidic output pressure signal to an electrical signal, and (4) an electronic control unit to accept the transducer signal and to process and scale it as required by the overall control system that is fed by this rate-sensing circuit. Figure 20 shows typical hardware for this rate-sensing application.

Figure 19. Fluidic pressure-regulating system.

Figure 20. Fluidic rate-sensing hardware.

[12] *L. J. Banaszak and W. J. Posingies, Hydrofluidic Stability Augmentation System (HYSAS) Operational Suitability Demonstration, Applied Technology Laboratory, USAAMRDL-TR-77-31 (October 1977).*

[13] *C. L. Abbott et al, A Study of Fluidic Gun Stabilization Systems for Combat Vehicles: Final Report, AiResearch Manufacturing Co. of Arizona, contract with Harry Diamond Laboratories, HDL-CR-80-100-1 (April 1980).*

Another fluidic device that uses second-generation fluidics is the fluidic capillary pyrometer (FCP).[14] The principle of operation for the FCP is analogous to the operation of an electronic resistance thermometer. In this system, the sensing probe contains a temperature-sensitive resistor in the form of a capillary tube. A small flow of air (or any gas) is maintained through the tube. The fluid resistance of the capillary is directly proportional to fluid viscosity, which, in turn, is a function of temperature. Therefore, if heat is applied to the capillary, its resistance will change, yielding a pressure output as a function of temperature. Typically, this pressure change is quite small, making conventional transduction impractical. Consequently, the pressure changes are amplified using an LPA gain block; the amplified signal can now be read on a pressure gauge, transduced to an electronic readout, or interfaced into a control system. The probes can be made from any material that can survive the environment in which the temperature measurements are to be made. Successful tests of the FCP have been made in blast furnace cupolas (>1650 C), forging furnaces (>1425 C), Naval boiler flames (>1650 C), molten iron (>1540 C), and induction furnaces (>2300 C). Figure 21 shows typical FCP hardware, consisting of a probe and a control box that contains the fluidic circuit and readout. Although the FCP was developed for military use, it has potentially even greater use in the civilian sector for controlling high-temperature processes, which will result in significant energy savings and improvement of the quality of the product.

Several servovalve manufacturers are now offering a more reliable product by using fluidics in the first stage of two-stage valves. Two new, high-performance aircraft—the Air Force F-16 and the Navy F-18—are using these fluidically controlled servovalves in several of their subsystems.

6. CONCLUSIONS

The technology known as fluidics is quietly advancing into commercial and military use. The advantage of this techonology's high reliability has been conclusively demonstrated from data on the air-driven system on the DC-10 and the hydraulically driven system on helicopters. The advent of the laminar proportional amplifier has resulted in fluidic systerns with more precision control—resulting in an increase of potential use of this technology.

Fluidics has now been accepted as a viable technology for military applications and for commercial use. It is expected that the coming years will find more widespread use of this advancing technology.

[14] *R. M. Phillippi and T. Negas, A Preliminary Industrial Field Evaluation of the Fluidic Capillary Pyrometer, ASME Publication G00177, 20th Anniversary of Fluidics Symposium (November 1980).*

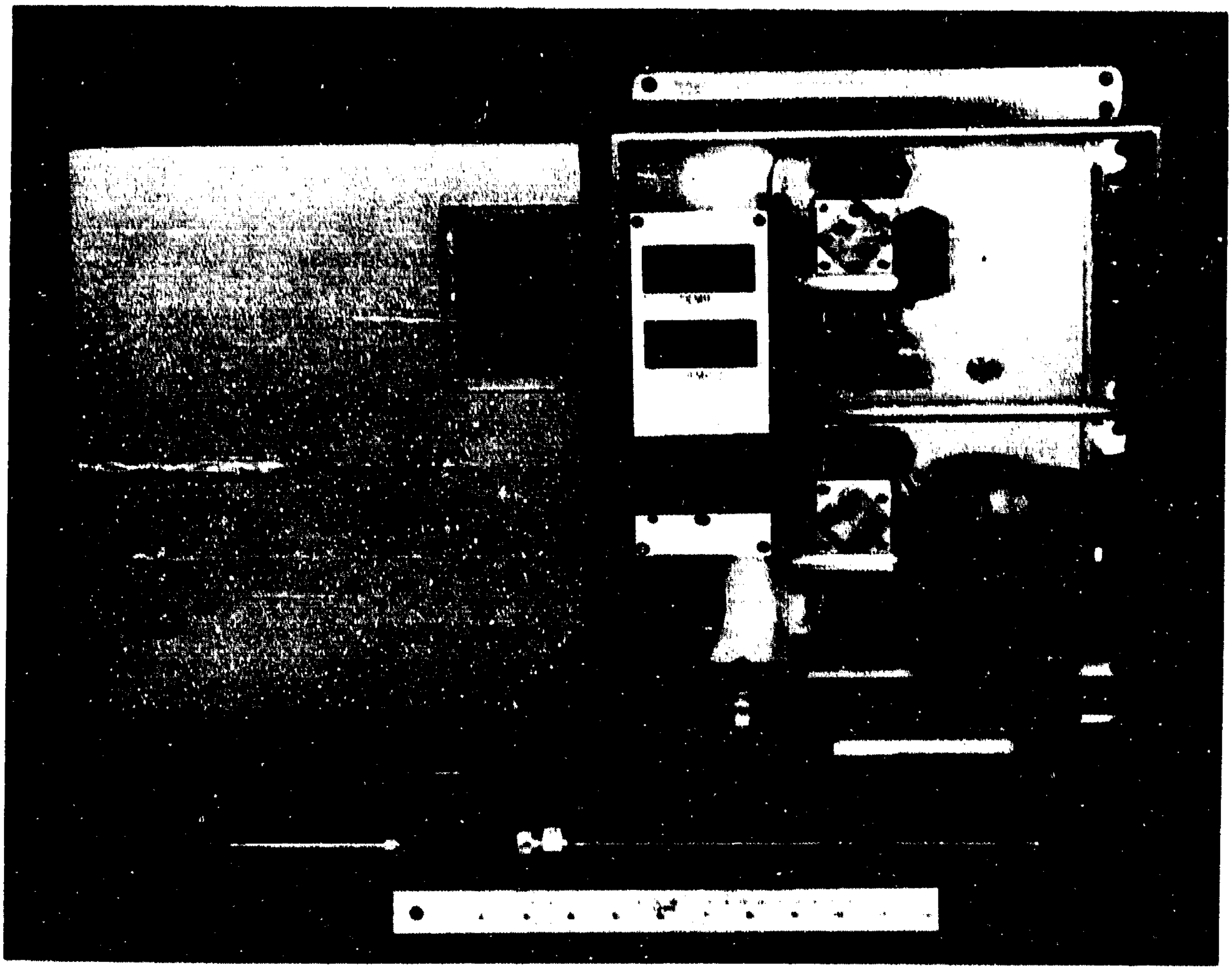


Figure 21. FCP hardware.

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